

FRACTIONATION BY A MODIFIED
ELUTRIATION (FELVATION) TECHNIQUE

A THESIS

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The Faculty of the Graduate Division

by

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SUMMARY

By Stokes' law, particles settle in a quiescent liquid at a rate directly proportional to the square of their diameter. Accordingly, the upward movement of a liquid inside a vertical column has long been employed to fractionate powders according to particle size. The technique is termed elutriation. By adjusting the rate of liquid movement, different size particles can be caused to rise or fall, and, hence, a series of particle size fractions can be obtained.

Simple elutriation does not produce a sharp separation, however, because of differences in flow velocity across an open tube. Better separation has been shown recently to be attainable if a screen is placed across the column and the flow rate adjusted so that particles just smaller than the screen openings will be carried upward. The screen acts to make the flow rate more nearly uniform and serves as a go-no-go valve for particles that can pass through it. The new technique has been called felvation.

In this thesis the use of felvation was examined as a means for making the operation easier by arranging various size columns and screens with different size openings in series. Sharper fractionation was also hoped to be achieved by employing a constant flow rate and using vibration throughout the felvation tower.

Both spherical and irregular powders were used in evaluating felvation column performance. Microscopic measurements were employed

for evaluation of the fractions and the completeness of the separation produced. Qualitative data on the separation of glass beads and flint silica powders on 44 μ , 53 μ , and 62 μ sieves are included. Fractionation by screening and by elutriation were also examined in order to compare the results for irregular powders with felvation.

It was found that constant-flow felvation is a valuable technique, providing a sharp and clean separation in an easily handled operation. It is superior to elutriation in that shorter operation time is required and the results are more readily predictable. Also constant-flow felvation is superior to dry screening in that the very fine particles are more easily removed.

CHAPTER I

INTRODUCTION

The efficient fractionation of fine particles is of considerable importance in the manufacture of products requiring powdered intermediates and in the analysis of powders. Two main processes for fractionating powders are sieving and elutriating.

Sieving is applied in industry to a very large tonnage of powdered materials and is frequently used for the size analysis of such materials in the laboratory, both for research and for the control of industrial processes. In sieving, particles are fractionated by separating them on a screen containing uniform apertures that permit the finer particles to pass through. There are several limitations in the technique. First, the process is subject to an exponential type decay of the rate of passage of powder through the sieve.^(1,2,3) Second, the sizes of apertures in sieves are not entirely uniform throughout. Instead, they exhibit a distribution of sizes.^(1,2,3) Finally, because the sieve must serve not only as a go-no-go gauge but also as a support for the powder, an unnecessary strain is put on the sieve which imposes unwarranted strength requirements on its structure. In spite of these limitations, the process of sieving is the most convenient method for grading powders above about 75 microns in diameter and may even be extended to 10 microns or less by the use of micromesh sieves.⁽⁴⁾

Elutriation is the process of separating powders into fractions of different mean diameter by suspending the particles in a moving fluid; many types of elutriators have been described.⁽⁵⁻⁹⁾ Theoretical

difficulties with this type of process are, first, the validity of Stokes' law, i.e., Stokes' law is valid for only a certain particle size range. Second, the shape and surface roughness of the material may cause variation between the calculated diameter and the actual diameter of the particles. Much work has been directed^(10,11) toward correlation of actual and predicted sizes, but to date no precise quantitative method has been devised. Third, it is difficult to obtain steady flow conditions. The presence of turbulence or convection currents contributes a source of error.⁽¹²⁾ Fourth, variation in the flow velocity across the column causes errors. Due to the parabolic shape of the flow velocity distribution, the average velocity is exactly half of the maximum velocity in all instances where viscous flow prevails.⁽¹³⁾ This produces a large variation in the size of particles that will be suspended by the flow. Finally, a practical difficulty experienced with very fine particles is that the fluid flow rate required to fractionate a powder is very low and several days can be required to achieve fractionation.⁽⁶⁾ Over such a protracted period, it is often difficult to maintain thermal isolation and stability for the equipment and to hold steady flow rates.

To overcome these disadvantages, a new process was devised in which the advantageous aspects of sieving, elutriation, and fluidization were combined. The technique was given the name "felvation" by Kaye and Jackson.⁽¹⁴⁾ In their work a tube of uniform diameter was used, the flow rate being changed according to the progress of separation. However, the completeness of the separation obtained was not defined analytically.

In this thesis the use of felvation is further explored for the purpose of (1) making the operation easier by arranging various size columns and screens with different openings in series under a constant flow rate instead of a varying flow rate, and (2) producing sharper fractionation by the use of vibration throughout the felvation tower. The "goodness" of the separation achieved was examined and compared with that attainable by other means.

CHAPTER II

THEORY

According to Stokes' law, the settling velocity of a spherical particle in a fluid is given by the equation

$$V_s = \frac{d^2(\rho_p - \rho_f)g}{18\mu} \quad (1)$$

where

V_s = settling velocity

d = diameter of particle

ρ_p = density of particle

ρ_f = density of fluid

μ_f = viscosity of fluid

and g = gravitational constant

The volumetric flow rate is given by

$$W = \frac{\pi D^2}{4} V_s \quad (2)$$

where

W = volumetric flow rate

D = diameter of tube

and V_s = fluid velocity (equal at equilibrium
to the settling velocity)

By combining equation (1) with equation (2), the diameter of the fluid container is related to the flow rate that will just suspend a particle by the equation

$$D = \sqrt{\frac{72\mu}{\mu(\rho_p - \rho_f)g}} \frac{\sqrt{W}}{d} \quad (3)$$

Letting $K = \sqrt{\frac{72\mu}{\mu(\rho_p - \rho_f)g}}$ the value of which is established by the properties of the fluid and the particles

$$D = K \frac{\sqrt{W}}{d} \quad (4)$$

from which it can be seen that Dd is a constant when a constant flow rate is employed.

In an operation using spherical glass beads as the particles and water (at 25°C) as the carrying fluid, the properties of which are:

$$\rho_p = 2.50 \frac{g}{cm^3}$$

$$\mu_f = 8.9 \times 10^{-3} \frac{g}{cm \text{ sec}}$$

$$\rho_f = 1 \frac{g}{cm^3}$$

$$g = 980 \frac{cm}{sec^2}$$

the value of K is

$$K = 1.18 \times 10^{-2} \text{ cm}^{1/2} \text{ sec}^{1/2}$$

Therefore, the diameter of the fluid column is directly related to the flow rate and the diameter of the particles by:

$$D(\text{cm}) = 15.2 \frac{\sqrt{W \left(\frac{\text{ml}}{\text{min}} \right)}}{d(\mu)} \quad (5)$$

By this relation, if it is assumed that the following diameters of particles are separated in each of four column sections, the diameters for the columns* are

$d_0 = 62.0\mu$	$D_0 = 6.35\text{cm}$
$d_1 = 51.3\mu$	$D_1 = 7.68\text{cm}$
$d_2 = 44.2\mu$	$D_2 = 8.89\text{cm}$
$d_3 = 31.0\mu$	$D_3 = 12.69\text{cm}$

Then, the appropriate flow rate is calculated to be

$$W = 671 \frac{\text{ml}}{\text{min}}$$

In the tests in which irregular flint silica powders and water were employed it was assumed that the particles were of spherical shape even though the sorting depends upon the shape as well as the size of particles. Appropriate values for this case were

$$\rho_s = 2.58 \frac{\text{g}}{\text{cm}^3}$$

* Originally the columns were built so that particles having diameters of $d_0 = 75\mu$, $d_1 = 58\mu$, $d_2 = 50\mu$, and $d_3 = 35\mu$ could be classified with a flow rate of 855 ml/min in each section. These settling diameters were found not to give good separation because of blockage of the screens. New diameters were then chosen along with a new flow rate. More about this will be mentioned in a subsequent section.

$$K = 1.15 \times 10^{-2} \text{ cm}^{1/2} \text{ sec}^{1/2}$$

$$D(\text{cm}) = 14.8 \frac{\sqrt{W \frac{\text{ml}}{\text{min}}}}{d(\mu)}$$

Assuming the same settling diameters as for the glass beads, the flow becomes

$$W = 710 \frac{\text{ml}}{\text{min}}$$

CHAPTER III

EQUIPMENT

The overall apparatus is shown schematically in Figure 1 and by a picture in Figure 2. The basic components are (1) a plastic tower up which the fluid flowed, (2) screens through which particles either passed or were retained, (3) sampling tubes by which fluid containing particles was withdrawn, (4) a voltage stabilizer, (5) a pump, (6) a filter, (7) a flow meter, (8) a particle supplying device, (9) an observation tube, (10) a water reservoir of 40 liters, and (11) the ultrasonic generator.

Tower

This unit consisted of four sections, designated Sec-0, -I, -II, and -III from the bottom, having the detailed dimensions shown in Table 1. The columns were fabricated by expanding plastic tubes of 2.50, 3.02, and 3.50 inches I.D. with a heat gun using a lathe and special mandrels. Sec-0 was longer than the others so that the particle concentration in it would not be too great. Sections were connected by clamping the flanges of each between two rubber plates with a sieve between them as shown in Figure 3. The diameter of each sieve was approximately 3 and 1/4 inches and the outer diameter of all the flanges was 3 and 3/4 inches.

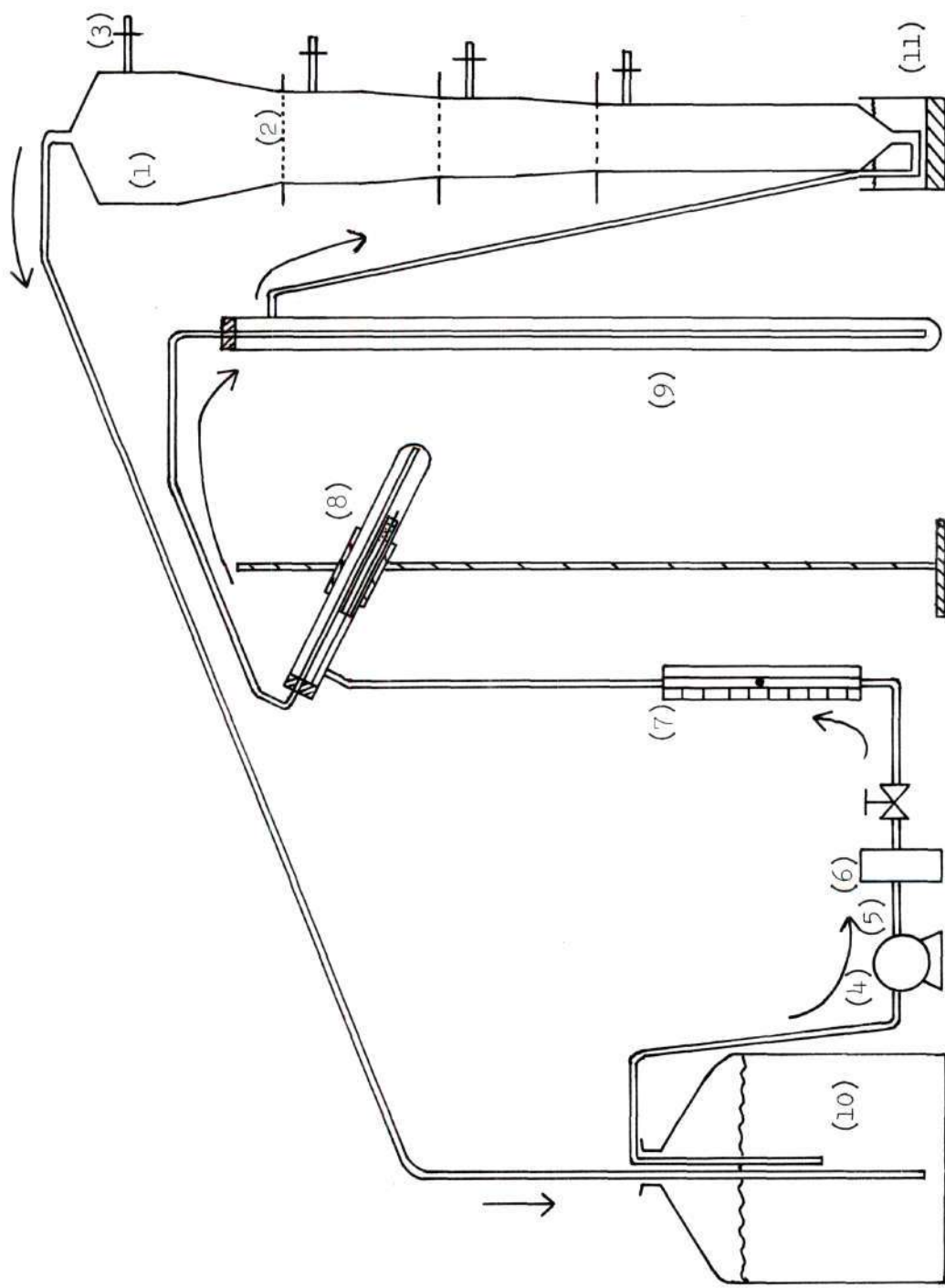


Figure 1. Schematic Diagram of Felvation Apparatus.

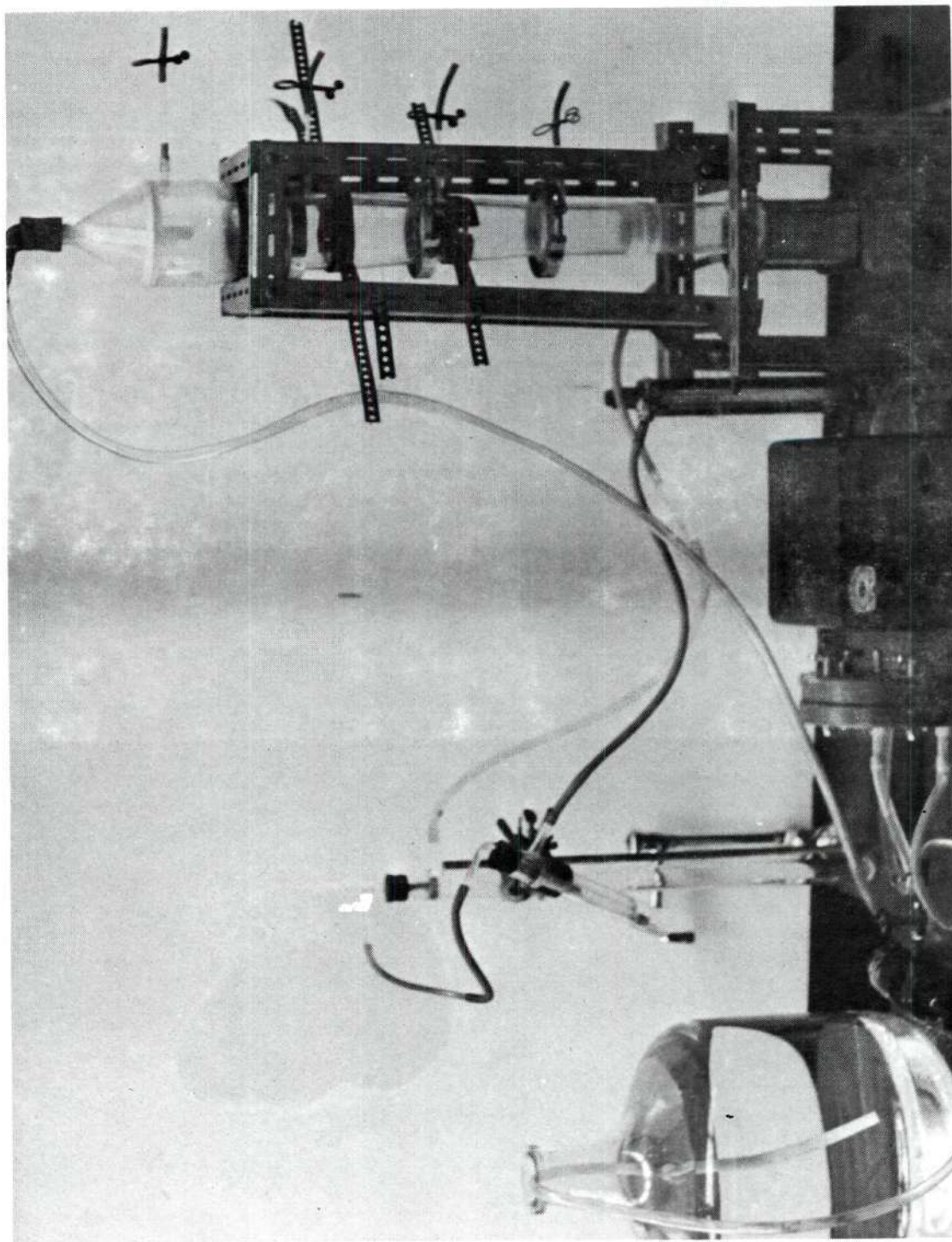


Figure 2. Picture of System.

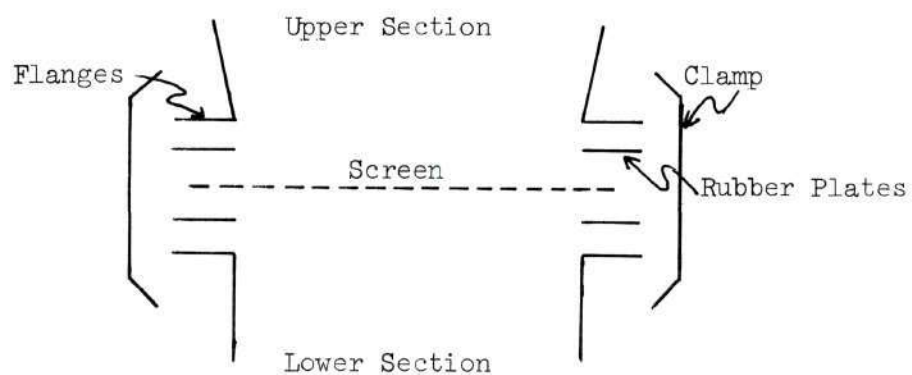
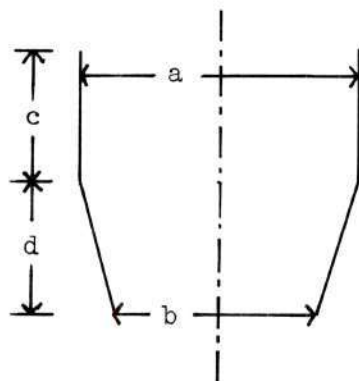


Figure 3. Method of Joining Column Sections.

Table 1. Dimensions of Each Column

	$\frac{a \text{ (ID)}}{\text{(inches)}}$	$\frac{b \text{ (ID)}}{\text{(inches)}}$	$\frac{c}{\text{(inches)}}$	$\frac{d}{\text{(inches)}}$
Sec 0	2.5	2.5		13 (altogether)
Sec I	3.02	2.5	3	3
Sec II	3.5	3.02	3	3
Sec III	5	3.5	3	4



Screens

U. S. Standard sieves of 250, 270, and 325 mesh were employed. They were obtained from The W. S. Tyler Co., Cleveland, Ohio.

Ultrasonic Generator

This equipment, Model NT-401, was manufactured by the Narda Ultrasonic Corporation, Westbury, New York. It operated at a frequency of 90 kilocycles and drew 40 watts of electrical energy.

Dry Sieving Equipment

A Sonic Sifter, Model L-3, manufactured by the Allen-Bradley Corp., Milwaukee, Wisconsin, was used. It operated at a frequency of 60 cycles.

Feeding Device

This system was built so that powders could be fed to the column at a controlled rate. It consisted basically of a test tube having a smaller glass powder container in it and a feeding tube that extended nearly to the bottom of the test tube. As shown in Figure 5, tilting the system caused powder to spill from the container where it could then be entrained and carried into the tower. The outer test tube had an inside diameter of 1 and 1/4 inches and was 10 and 1/2 inches long. The container tube had an inside diameter 5/8 inch in I.D. and was 5 inches long.

Sampling Arrangement

The sampling arrangement was composed of a 1 and 1/2 inch long plastic tube of 3/4 inch I.D. attached to each tower section, a glass tube 6 inches long having a 1/8 inch I.D., a short piece of rubber tube,

and a clamp. A diagram of the arrangement is shown in Figure 4. To sample, the glass tube was pushed in toward the center of a section by sliding it through the rubber tube. The clamp was then released, discharging a sample from the center section of the tower.

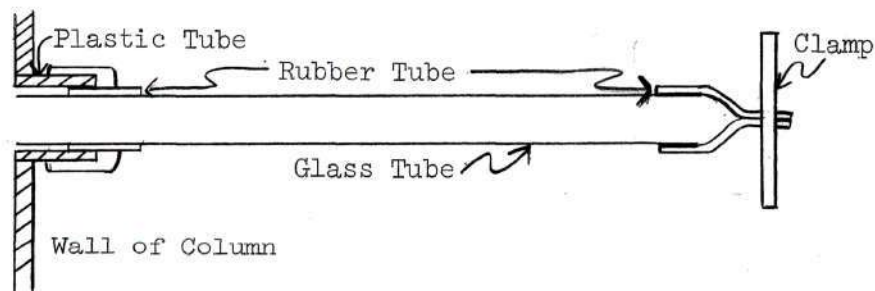
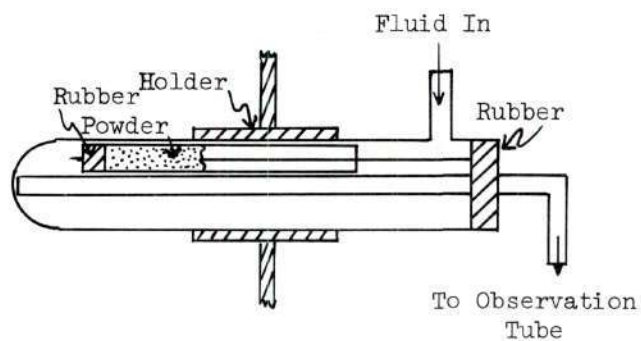


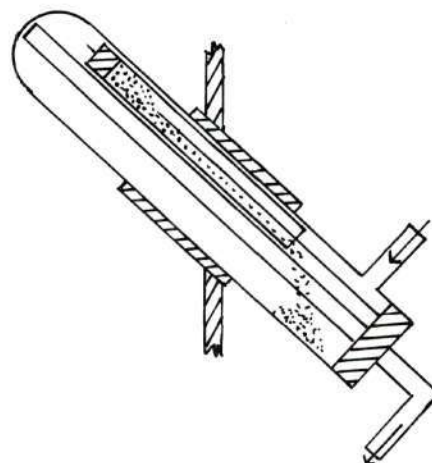
Figure 4. Sampling Tube.

Observation Tube

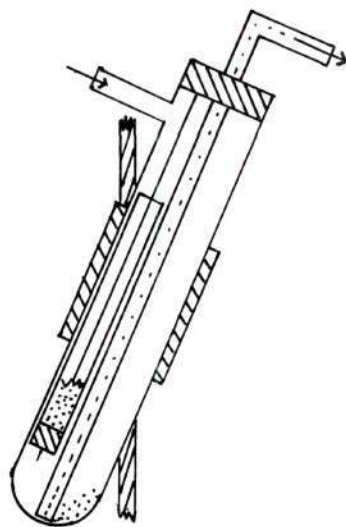
A section of glass tube of 1 and 1/4 inch I.D. and 28 inches long was incorporated in the system between the feeder and the first section of the tower so that the incoming feed could be observed and adjustments could be made in the feed rate.



- (a) Maintaining the Tube Horizontal Insured that no Powder Escaped from the Container.



- (b) When the Tube was Inclined as Shown, the Powder Moved to the Outer Tube.



- (c) When the Tube was Inclined as Shown, the Carrying Fluid Picked up the Powder and Conveyed it to the Observation Tube.

Figure 5. Powder Feeder.

CHAPTER IV

EXPERIMENTAL PROCEDURE

Operation for Fractionation by Flotation

An experiment was initiated by switching on the pump. While water was filling the tower, care was taken to prevent bubbles from entering the system. If bubbles were introduced into the system from any connecting tubing, they eventually collected under the screens, reducing the area of the screen and hence the separation efficiency. Water was left at least overnight in a reservoir before using so that dissolved air, which was found to come out particularly when the water passed through the screens, could escape.

After all systems were filled with water, the powder feeder was tilted, and powder to be fractionated was started flowing to the tower. The ultrasonic generator was switched on before powder particles reached the first screen. Powder was supplied at only a moderate rate because, if too many particles tried to pass at once, they blocked the screen apertures preventing good separation.

The rate at which powder was supplied could be observed through the observation tube and controlled according to the concentration there. The powder feeder was turned horizontal when the concentration needed to be reduced, and, when more powder was needed, the supplier was turned more nearly vertical, according to the amount of powder required.

Powder feeding was continued for about one hour. During the

next fifteen minutes the water flow rate was held constant. During the entire first seventy-five minutes, called the "separation stage," fractionation was being caused to occur according to Stokes' law. The finer particles were carried away during this constant flow rate stage. For about the next fifteen minutes, the flow rate was increased to twice its previous rate and particles, which either could not or had not been carried up by the first flow, were given a greater upward driving force. As this stage is similar to the "rinse" period of a filter, it has been called the "rinsing stage". This rinsing served to remove remaining particles and to result in a cleaner fractionation. Rinsing was continued until no more particles could be seen rising from any of the screens. Sampling was started when this final stage of the fractionation was reached. Throughout the operation, particles flowing in the tower could be seen when viewed against a bright light.

Sampling was accomplished, first, by moving the sampling tube to the center of a section and by increasing the flow rate so that the flow rate of the water in the tower was not diminished because of the water removed by the sampling. Then water was drained through the sampling tube at a rate such that powders above the screens did not fall through them and, thus, were not sampled. These sampled particles were collected on millipore filters. About 500 ml of fluid were withdrawn. After drying the filters, the collected particles were transferred to glass slides for microscopic examination.

Evaluation of Fractions

The particle sizes produced by the felvation tower were measured with an optical micrometer, an especially useful method for evaluating

distributions having a narrow range. Individual particles were measured by this technique and, after a sufficient number of them had been examined, a number distribution was calculated.

As only one dimension of each particle was measured, the manner in which this one was chosen was extremely important. Many statistical diameters have been described.⁽²¹⁻²⁹⁾ The Feret⁽¹⁷⁾ diameter, defined as the greatest length of a line intercepted by the profile boundary and shown in Figure 6, was chosen for use in this thesis. It was selected because of its ease of measurement with an optical micrometer.

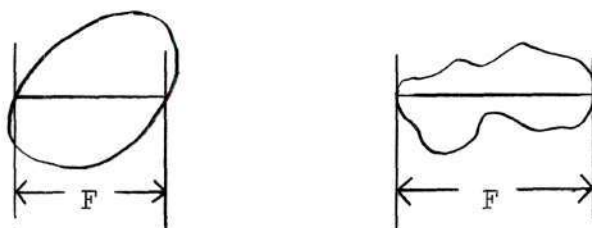


Figure 6. Illustration of Feret's Diameter.

The direction in which the greatest dimension is taken is of no consequence if the direction is maintained constant for all measurements. This diameter was used to evaluate individual particle sizes from the felvation tower and also from other means of fractionation mentioned later. A sufficient number of particles was measured at a magnification of 100X to give reproducible results, two hundred being an adequate number when the distribution is narrow.⁽²⁴⁾ Class intervals were chosen as ten units on the ocular micrometer scale which corresponded to an actual length of 3.40 microns as calibrated with a stage

micrometer. White light with a green filter was utilized to reduce eyestrain.

Investigation of Sieve Apertures

Even though every sieve is supposed to have a constant aperture size, each usually has an aperture size distribution.^(1,2,3) Therefore, in order to determine how the sizes of the apertures were distributed (effective aperture size) and how this distribution of aperture sizes affected the fractionation results obtained with the sieve, the second sieve, having nominally 53-micron openings, was investigated under the microscope by counting 200 apertures from ten different fields.

Fractionation by Dry Sieving and Elutriation

Studies of fractionation of flint silica by dry sieving and elutriation were made for comparison with felvation, because it is impractical at the present time to evaluate results obtained by felvation absolutely with irregular particles.^(10,11) With spherical glass beads an absolute comparison is possible; such a comparison was made as described subsequently. In the case of irregular particles, it happens that particles passing a sieve are measured microscopically to be larger than the screen aperture,⁽²⁵⁾ and hence a microscopic size distribution will not show a good correlation with sieve aperture size. This discrepancy comes from the shape of the powder particles and the way of choosing the diameter for microscopic measurement.⁽²⁶⁾ Therefore, fractionations by dry sieving and elutriation were obtained to show how good (or bad) were the results by felvation, measuring particles using Feret's diameter.

Fractionation by Dry Sieving

Three grams of flint silica powder (the optimum amount for the sieving device used) was placed on the top sieve of a nest of sieves of 250, 270, and 325 mesh in this order (the same sieves as used in felvation), and vibrated for 90 minutes, the same period of time utilized in the felvation operation. Fractions were obtained on the 270- and 325-mesh sieves; their particle sizes were measured microscopically, again employing Feret's diameter.

Fractionation by Elutriation

With all the sieves used in the felvation operation removed, four grams of flint silica powder, the same amount as used in a felvation test, was fed into the felvation tower in the same manner as in felvation. The feeding time was 60 minutes and the water was kept flowing for another 30 minutes. At the end of this time, fractions from each section of the tower were obtained and their particle sizes measured.

Fractionation by Best Dry Sieving

Besides the comparison with elutriation and dry sieving, the following test, constituting what might be called "ideal dry sieving", was made for another comparison. The size distributions obtained by this method are presumed to be those determined only by sieve-aperture sizes and the shape of powder particles. In other words, they are the ultimate size distributions obtainable using these sieves.

The original flint silica powder was first sieved for a preliminary period of four minutes on the 325-mesh sieve to remove most

of the fine dust. This sieve was then cleaned of the adhering fine dust and the powder residue, about 3.4 grams, was placed on the nest of sieves arranged, in order, 250, 270, and 325 mesh. The nest of sieves was vibrated for a period of eight minutes, each sieve was again cleaned, the residue was replaced, and each residue was vibrated by itself for other periods of six and 10 minutes. Finally, size distributions were made for both the six- and 10-minute fractions.

CHAPTER V

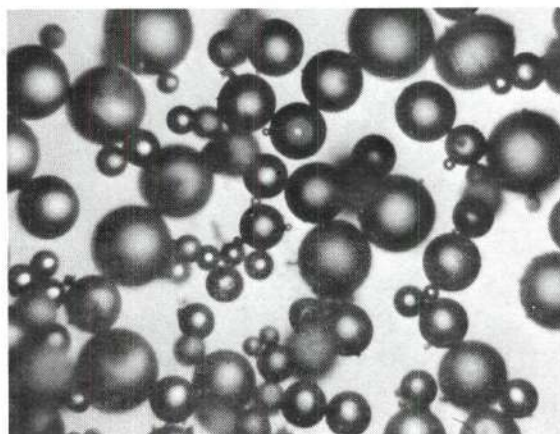
RESULTS AND DISCUSSION OF RESULTS

As described above, the fractions of glass beads and flint silica were measured microscopically employing Feret's diameter. The sizes obtained are photographically shown by Figure 7 and 8 at a magnification of 100X. Size distributions for glass beads are shown graphically by Figure 9 as a function of the percentage by number finer and on Figures 10, 11, 12, and 13 by histogram. On Figure 14 size distributions are given for flint silica as a function of the per cent by number finer.

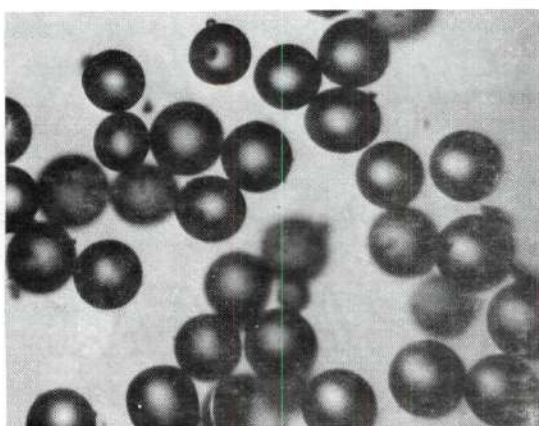
Spherical Particles (Glass Beads)

As may be seen from Figures 10, 11, 12, and 13, the results for glass beads show particles greater than the nominal sieve openings. In order to explain this, the size distribution of the 270-mesh sieve was measured; the results are shown on Figure 15.

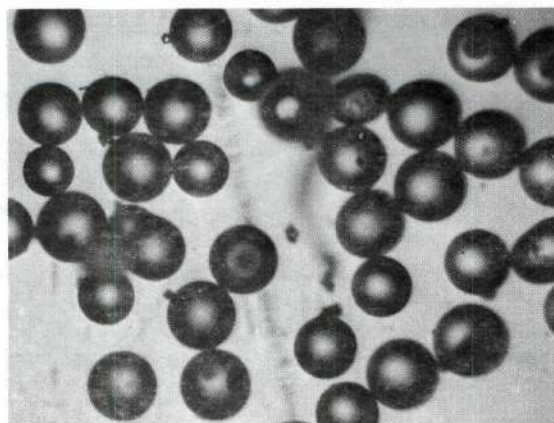
This figure shows that this sieve apparently has larger openings than the nominal size. It was found also that the largest opening of the sieve matched the largest particle obtained in Section II of the tower, i.e., particles passing a 270-mesh but not a 325-mesh sieve. Therefore, it can be said that even particles larger than the nominal opening, i.e., 53 microns, and collected between two sieves should be considered as passing-particles and included in the fraction to be expected from Section II. From this result, it is clear that other fractions should also be treated in the same way and particles larger



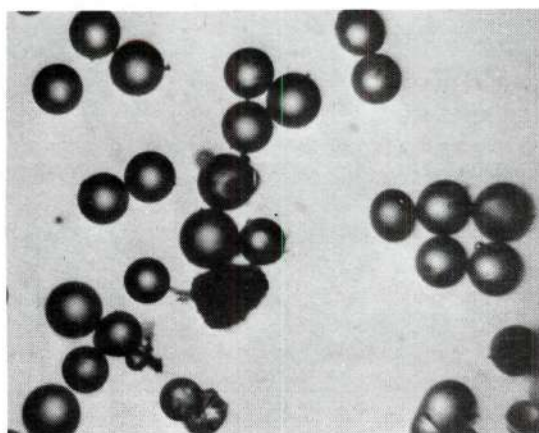
Original



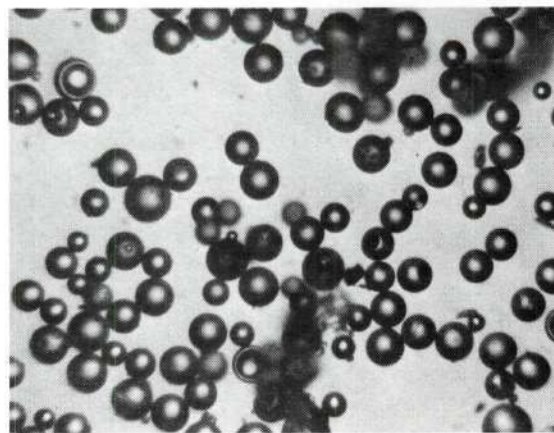
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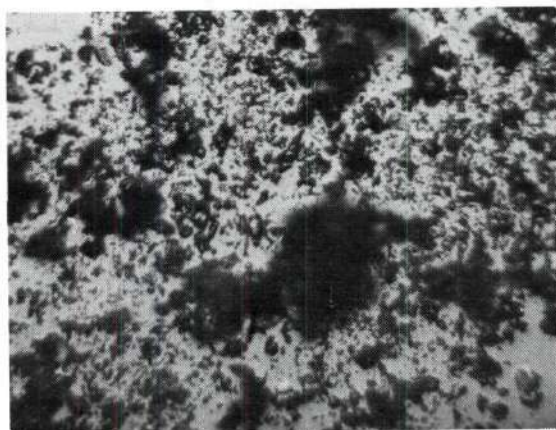


Sec II



Sec III

Figure 7. Glass-Bead Fractions 100X.



Original



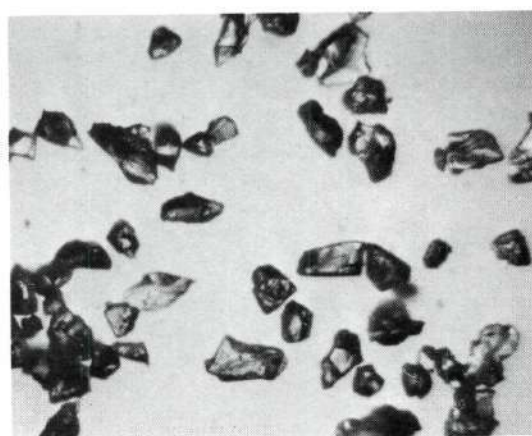
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Sec III

Figure 8. Flint Silica Fractions 100X.

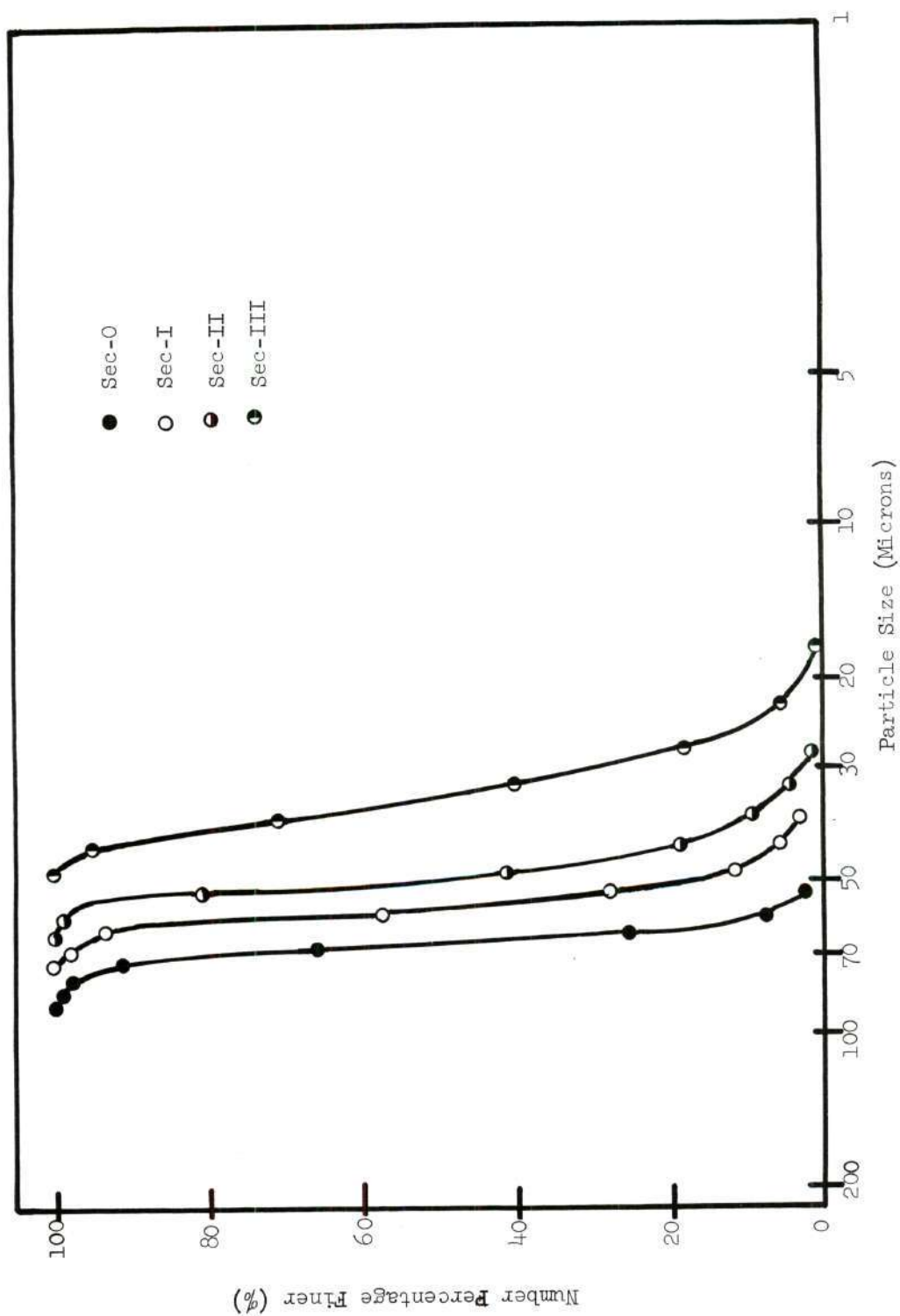


Figure 9. Size Distribution Curves for Glass Beads.

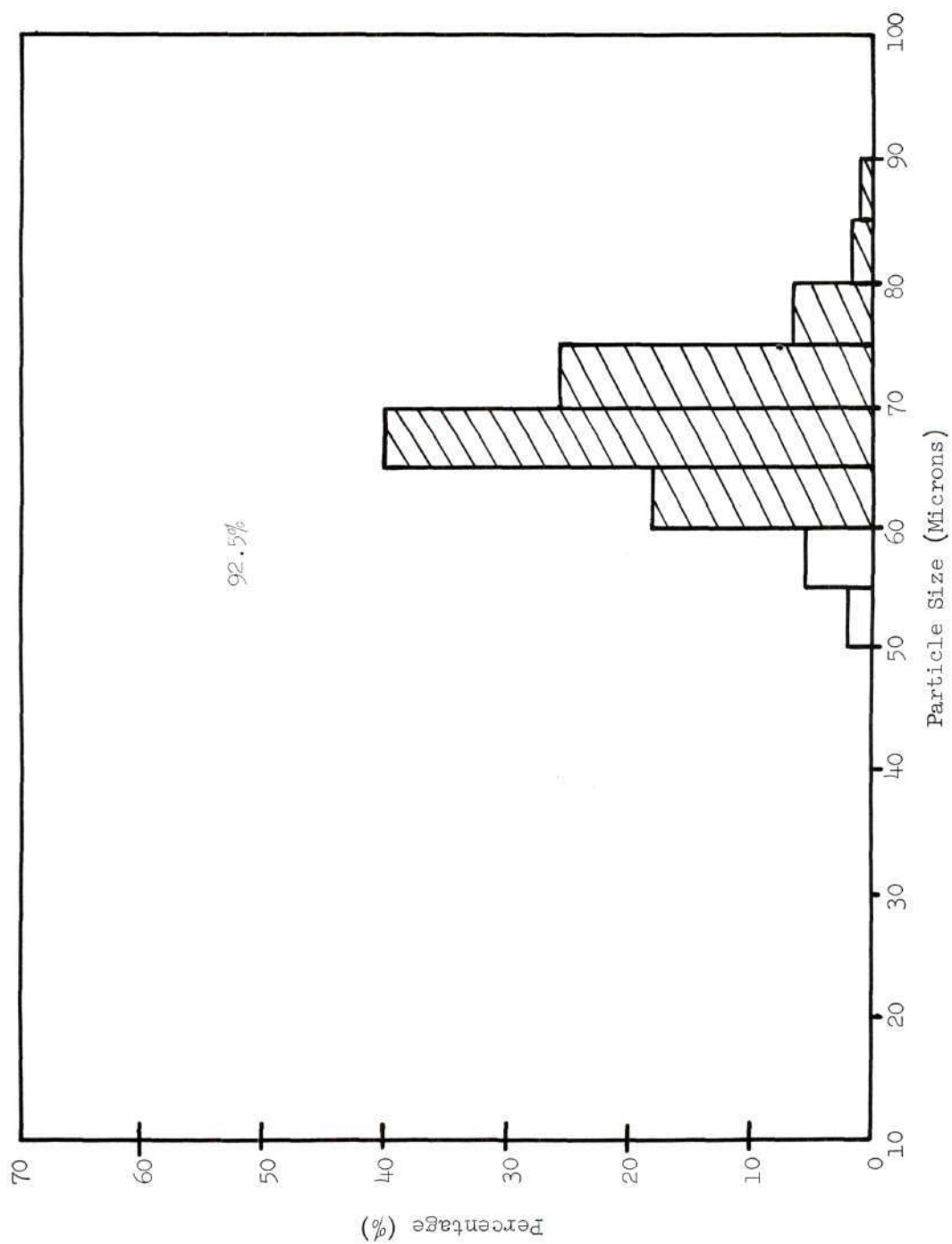


Figure 10. Histogram for Glass Beads from Section 0.

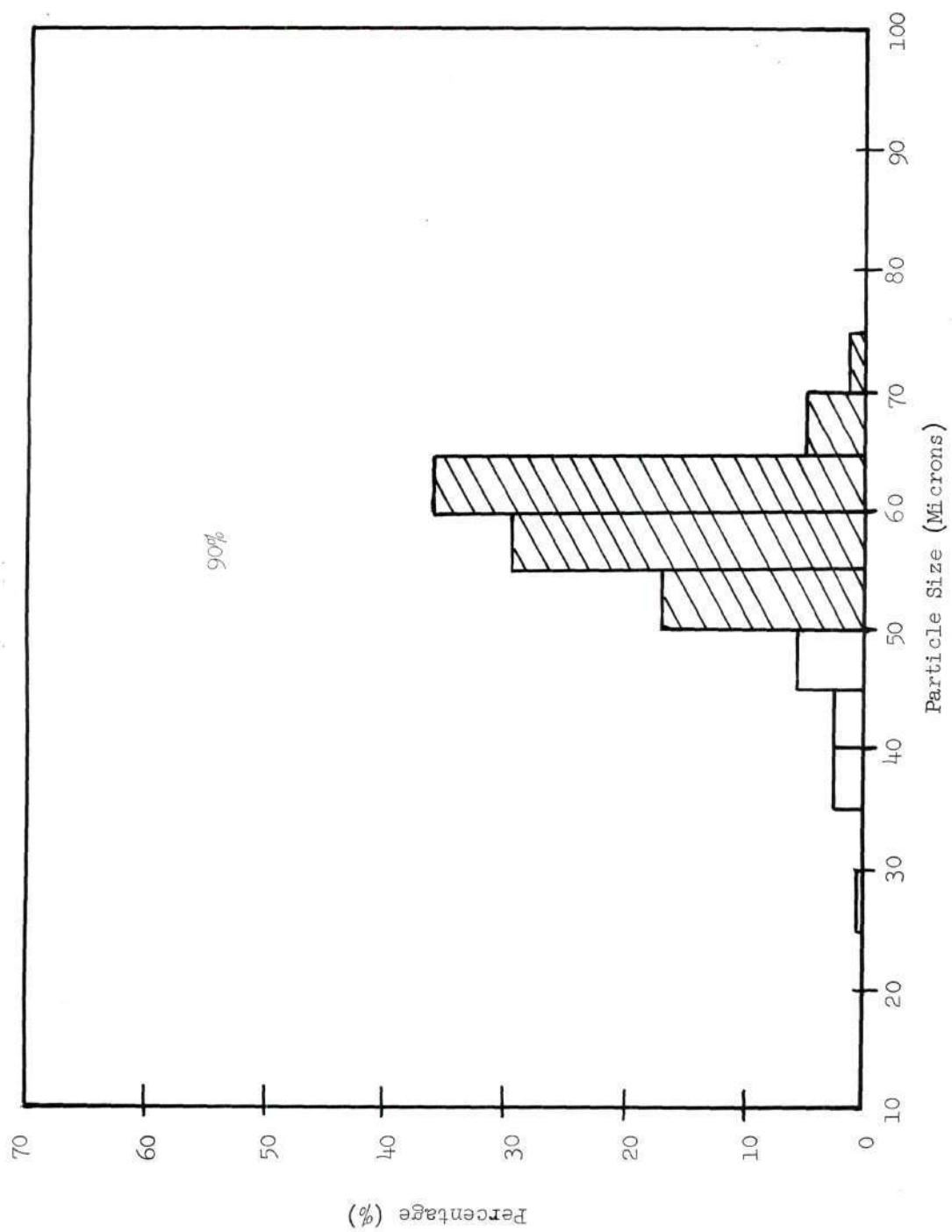


Figure 11. Histogram for Glass Beads from Section I.

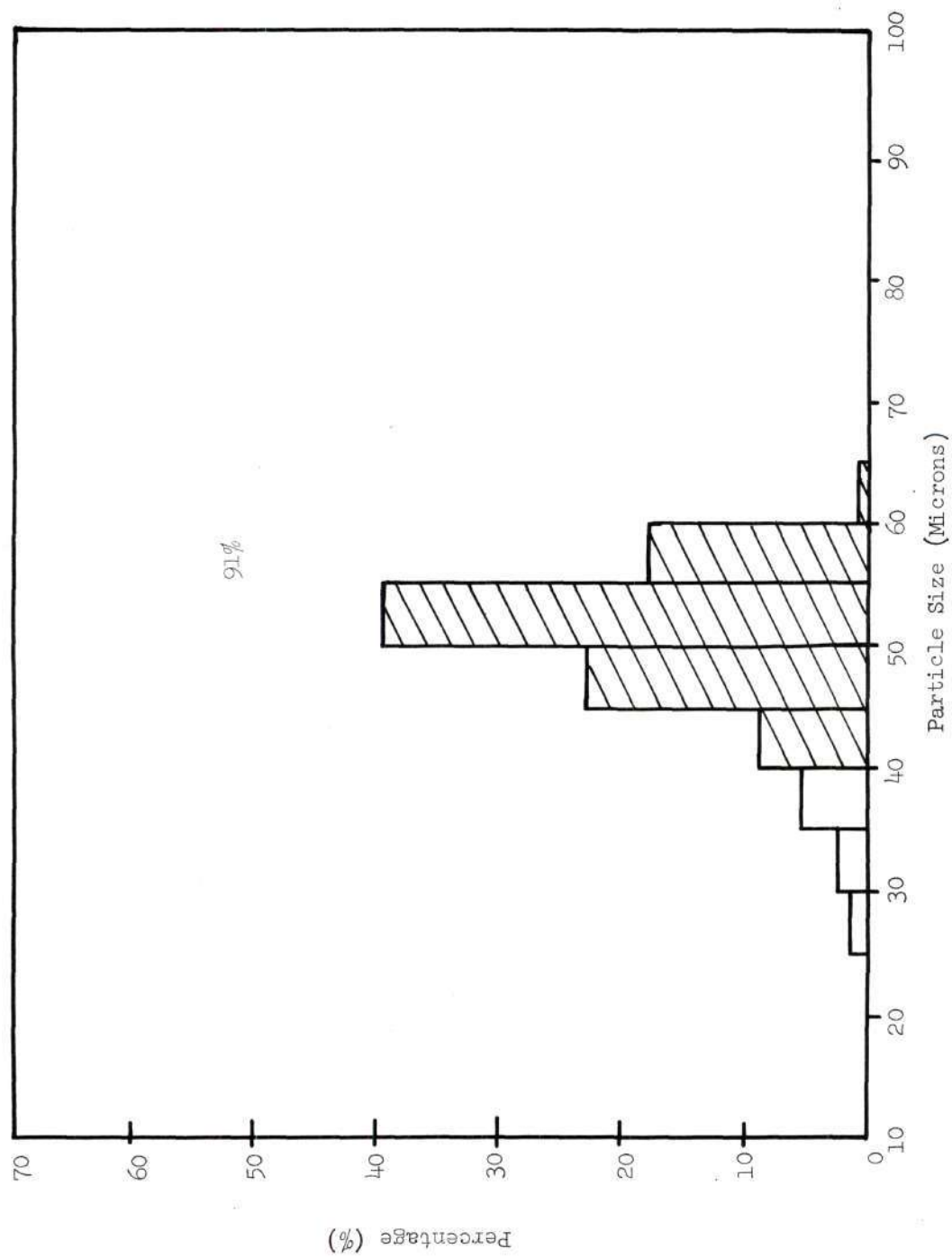


Figure 12. Histogram for Glass Beads from Section II.

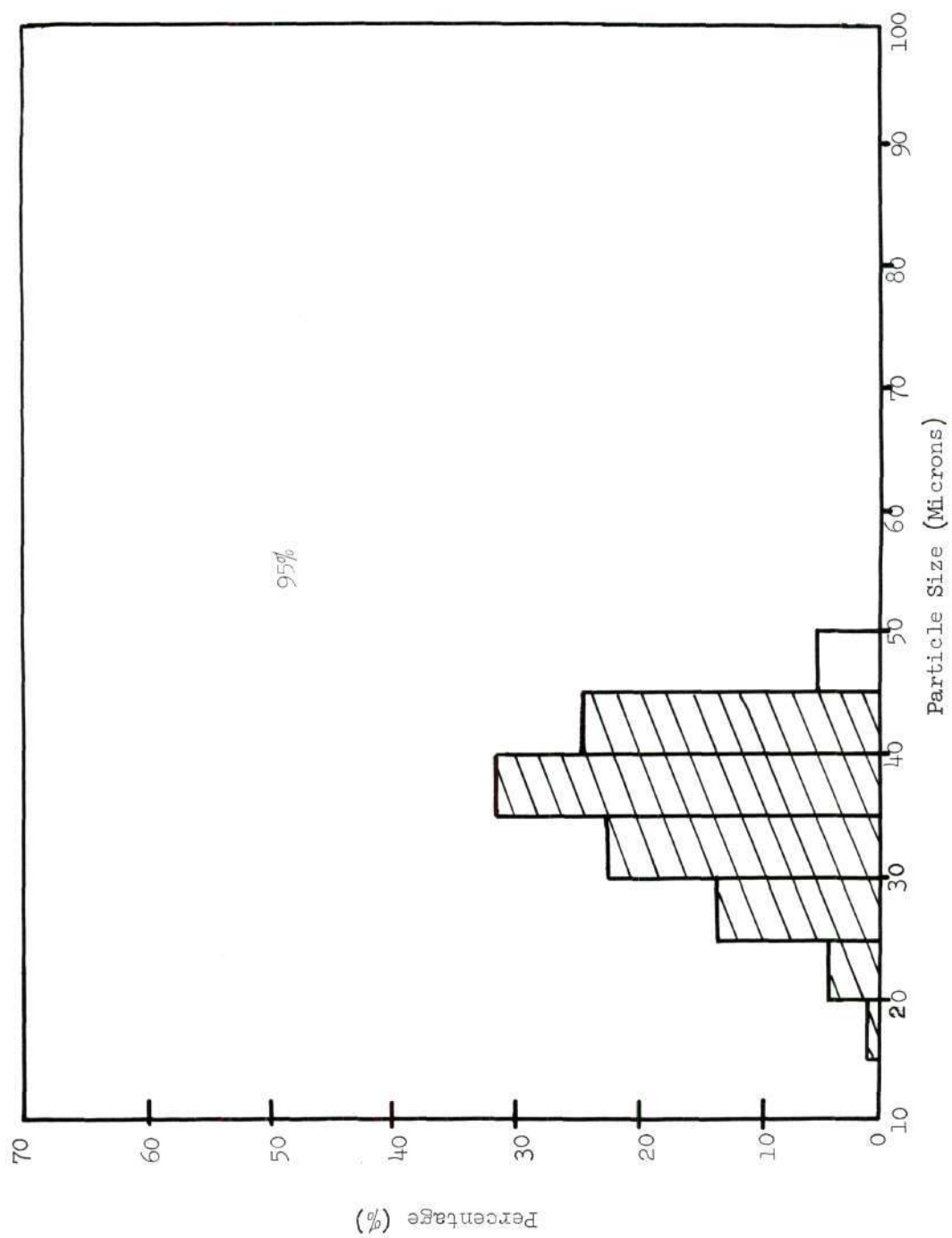


Figure 13. Histogram for Glass Beads from Section III.

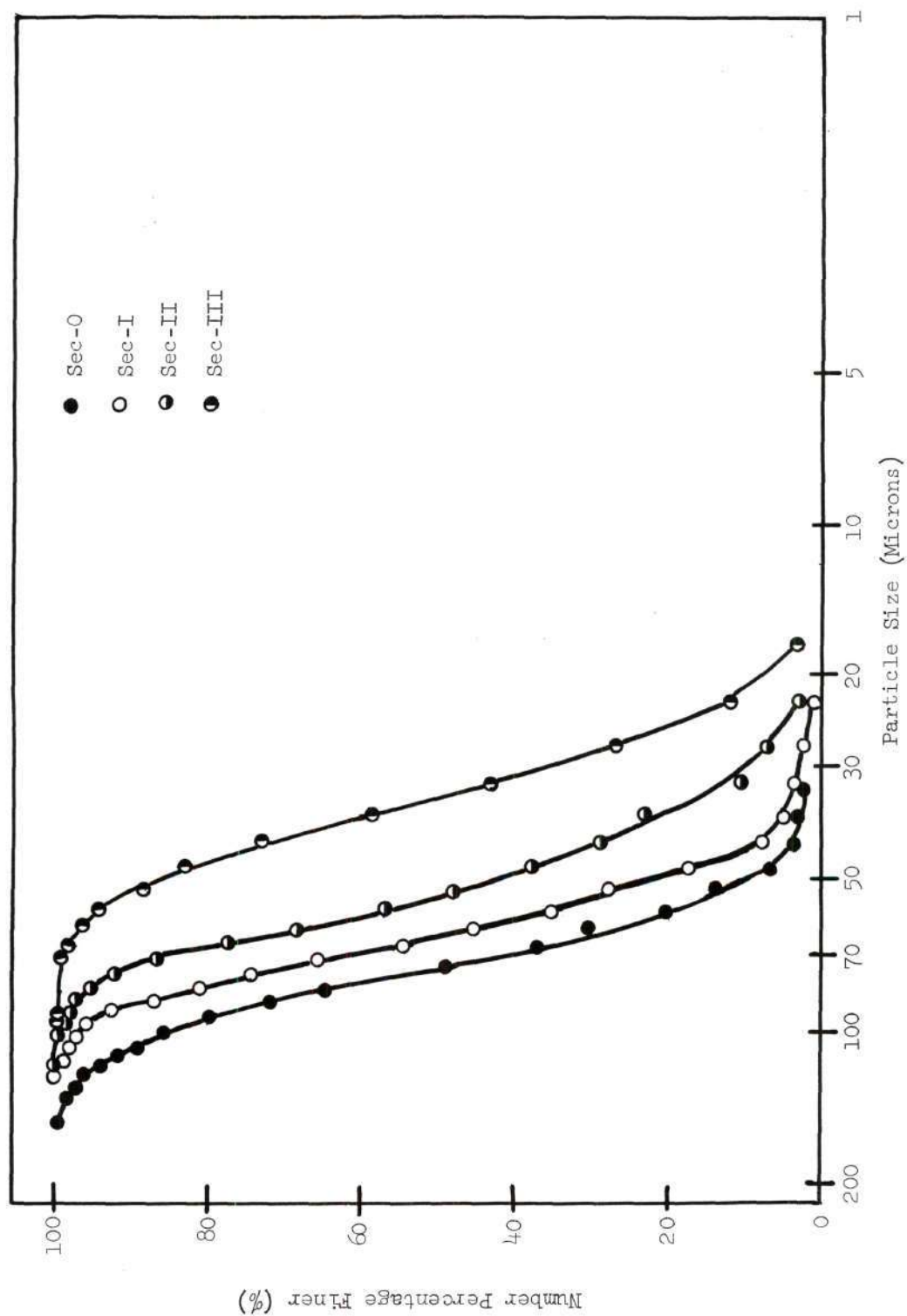


Figure 14. Size Distribution Curves for Flint Silica.

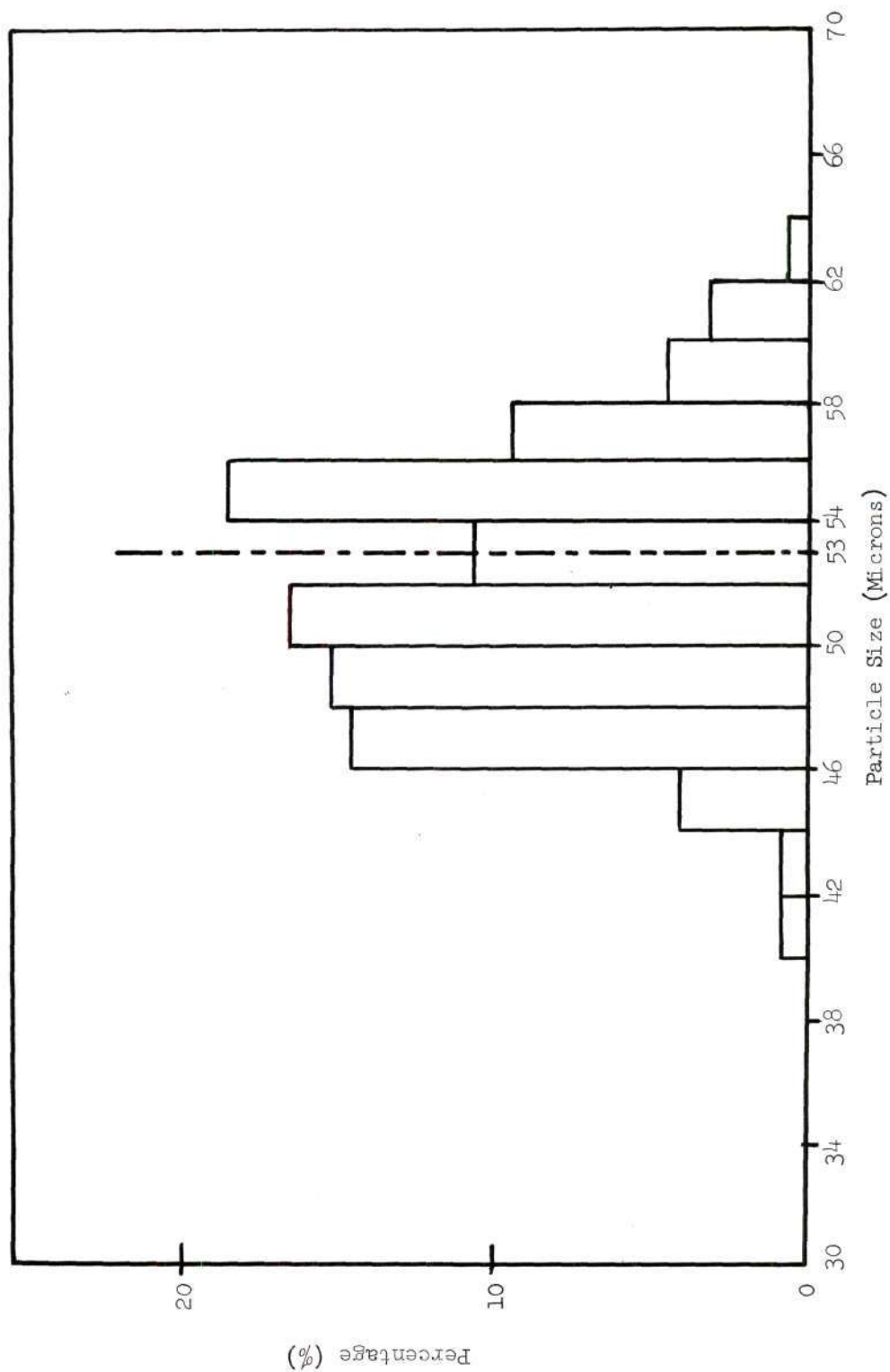


Figure 15. Opening Distribution for 53-Micron Sieve.

than the nominal opening of the sieve should be expected as far as the separation using screens is concerned.

The particles included in the expected range in each section are shown in Figures 10, 11, 12, and 13, and the percentages of particles falling in the range are also noted. These percentages are 92.5, 90, 91, and 95 for Sections 0, I, II, and III, respectively.

There can be seen particles smaller than the expected size on the figures, also. These are thought to be the ones that were attached to each other or to larger particles while in the medium but became separated when they were dried and moved from the filter to the glass plate for examination. This explanation is derived from the fact that most of the out-of-range, smaller particles could be seen in the vicinity of other similar size or larger particles when viewed with the microscope. Therefore, the results could have been improved for glass beads by using a more suitable dispersing agent.

Irregular Powder (Flint Silica)

As mentioned above, it is difficult to evaluate the results for irregular particles as was done for spherical particles. The size distributions obtained microscopically are dependent both on the shape of the powder and the way of measuring diameters.⁽²⁶⁾ Therefore, in evaluating these results it has been thought best to compare them with results obtained by other fractionating techniques and measured in the same manner. From the point of view that felvation is, in principle, a technique combining elutriation and dry screening, elutriation and dry screening results were chosen for comparison. "Ideal" dry screening as done for an absolute standard was also utilized.

The fractions obtained in column Sections I and II were compared because the fractions from Section 0 and III are not exactly identical in felvation and in dry screening. Fractions from Sections I and II can be under the same condition in both techniques, although in elutriation all fractions are under the same condition as in felvation. This is so because the fraction from Section 0 by felvation does not contain all particles larger than 250 mesh as the very large particles remain in the observation tube. The fraction retained on the 250-mesh sieve in dry screening includes all the particles larger than that sieve opening. The fraction in Section III from felvation does not contain all particles smaller than 325 mesh as the very small ones are carried away, while the fraction sampled under the 325-mesh sieve in dry sieving includes all smaller particles. These results are compared in Figures 16 and 17.

In the case of the best separation by dry sieving, particles smaller than 5 microns in diameter, which are not completely removed by dry sieving, ^(1,2,3) were not counted because these fine particles could not be found in the felvation fraction and the information needed from dry sieving relates to which particles can or cannot pass through a given sieve. In the case of spherical and smooth-surfaced particles, it is easy to establish whether or not a particle can pass the sieve, since particles larger than the screen aperture cannot pass and those smaller can pass. Irregular and rough-surfaced particles do not conform to this regularity because of shape. In other words, in a comparison of felvation and best dry sieving, the particles which should be taken into consideration are only those of near-mesh sizes.

The results of best dry sieving are shown in Figures 18 and 19.

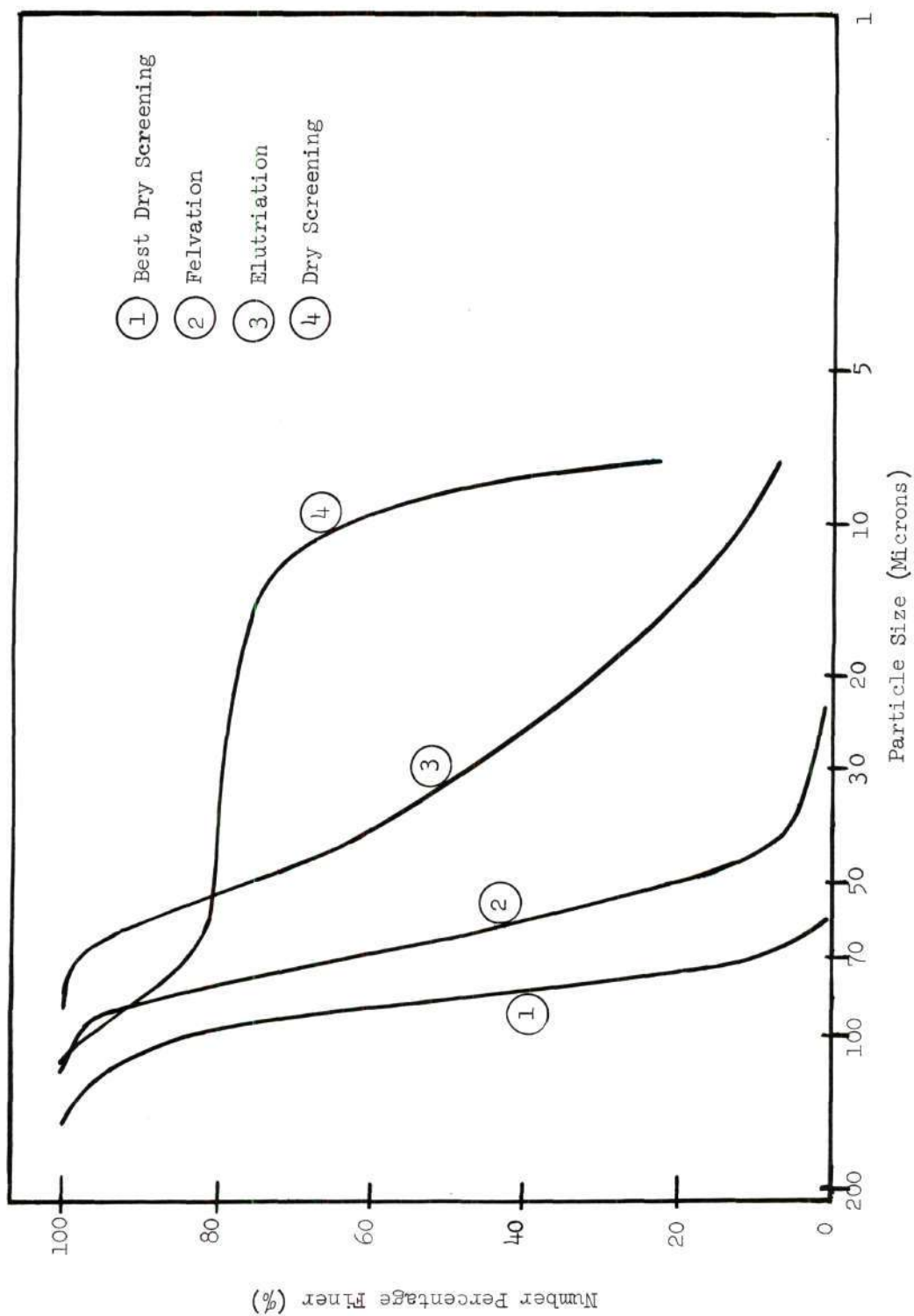


Figure 16. Comparison of Techniques for Section I.

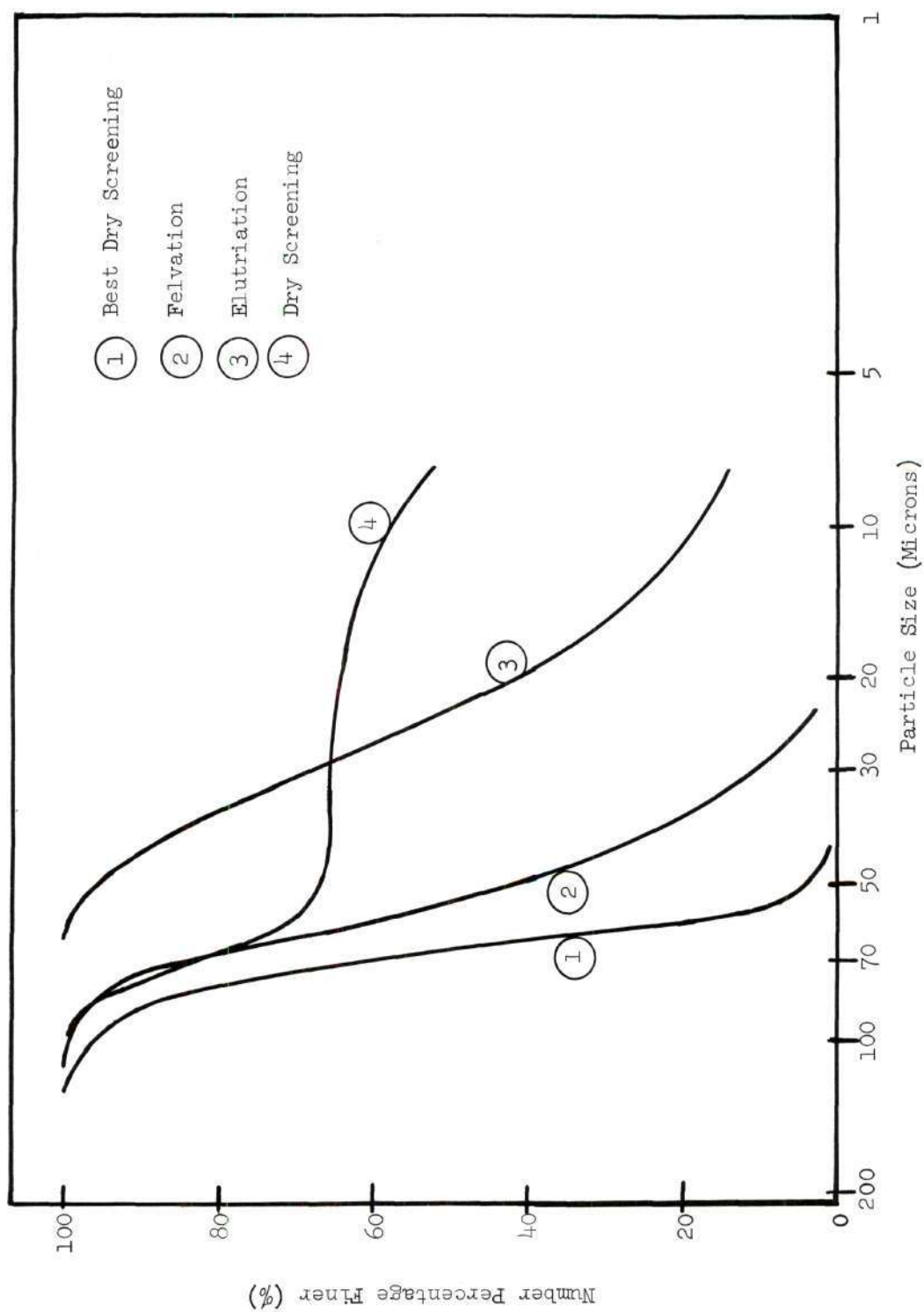


Figure 17. Comparison of Techniques for Section II.

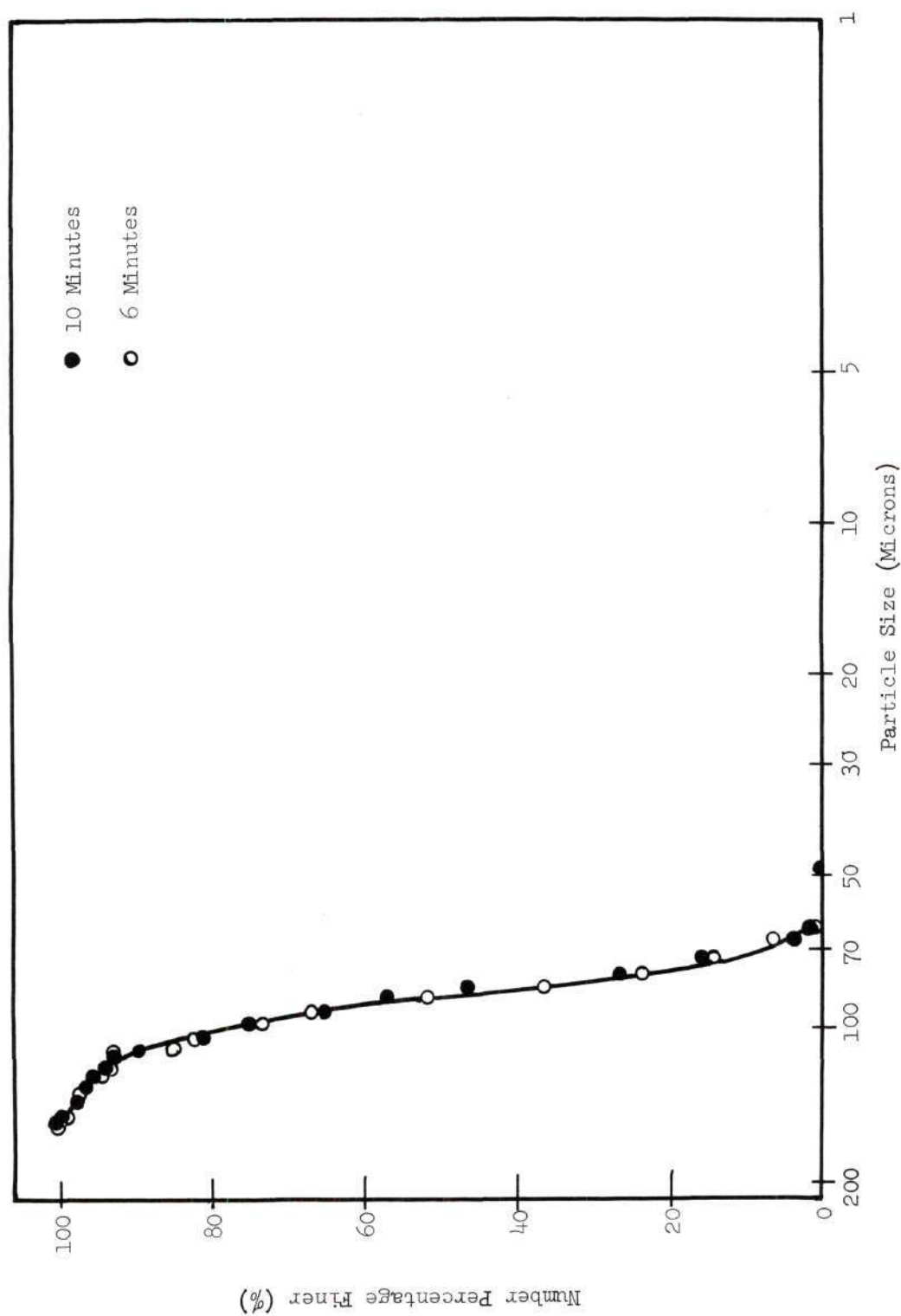


Figure 18. Size Distribution Curves for Best Dry Sieving with Section I. Sieve.

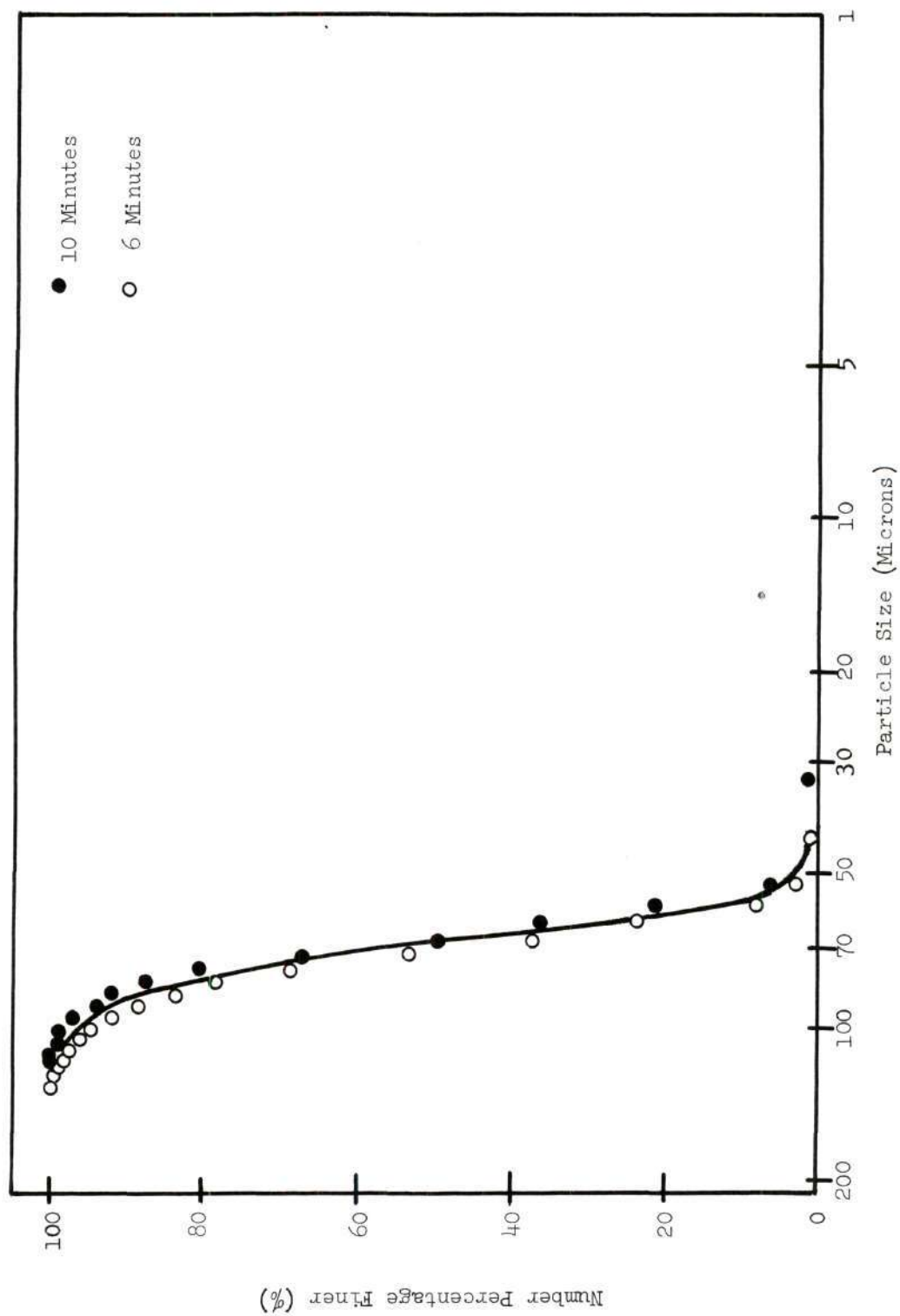


Figure 19. Size Distribution Curves for Best Dry Sieving with Section II Sieve.

The data show that size distributions after 6 and 10 minutes are nearly identical, which means that all particles that should pass through the sieve have already passed by this time. Therefore, this result can be identified as the best possible separation attainable with these sieves. Also in dry sieving and elutriation, fine dusts smaller than 5 microns in diameter were not counted as the results for them are apparently worse than for felvation in spite of neglecting fine dusts, i.e., the actual results are poorer than those shown in Figures 16 and 17.

From Figures 16 and 17 it is apparent that the fractionation obtained by felvation is much better than by dry sieving and elutriation and closer to that by best dry sieving. While elutriation gives a wide size distribution, dry sieving gives very good fractionation except for the small particles, hence is not entirely satisfactory. Fractionation by felvation compares favorably with the best separation obtained using the same sieves.

The discrepancy between the two size distributions from felvation and best dry sieving seems to arise from the influence of the frequency and the degree of the vibration used in felvation and in the shaking machine. Just how or why is not clear at this point.

In the elutriation technique, better results could be obtained with longer sections and longer operation times as well as a better operational technique. Usually the size distributions obtained cannot be predicted precisely because of the velocity variation of the fluid across the tube diameter⁽¹³⁾ and also because the separation does not follow Stokes' law exactly, particularly for irregular powders.⁽²⁴⁾ In addition, elutriation is very time-consuming.⁽⁶⁾ It further

requires well-established laminar flow and very steady flow rates.⁽¹²⁾

Through the experiments obtaining the fractionation for what was termed "ideal" dry sieving and also for standard dry sieving shown in Figures 16 and 17, it can be said that dry sieving is very good for near-mesh and large particles but it becomes difficult to make fine particles pass through sieve openings because of the van der Waals forces between particles.^(27,28)

Compared to elutriation and dry sieving techniques, felvation gives sharper fractionation, and it does not require as long an operation time as elutriation. It also provides very good means for removing the very fine particles which cannot be taken out by dry sieving techniques. These factors arise because in felvation, as in elutriation, powders can be easily dispersed with the help of the conveying medium. In this process fine particles that might adhere to coarser particles⁽²⁹⁾ are separated and are carried away. Particles examined after felvation were found to have very clean surfaces. The size distributions obtained by felvation can be predicted better from a knowledge of best dry sieving if done before the felvation operation with the same sieves. Results calculated by means of Stokes' law usually lead to a discrepancy in the results.^(10,11,24,30,31,32) The operating method is important in obtaining good separation by felvation. The rinsing stage, especially, is important in removing still-remaining but passable particles. The increased flow rate is one big advantage of felvation. The relation of flow rate with time is shown in Figure 20 for operation with a given amount of a particular powder. The time period must, of course, vary according to the powder and its amount.

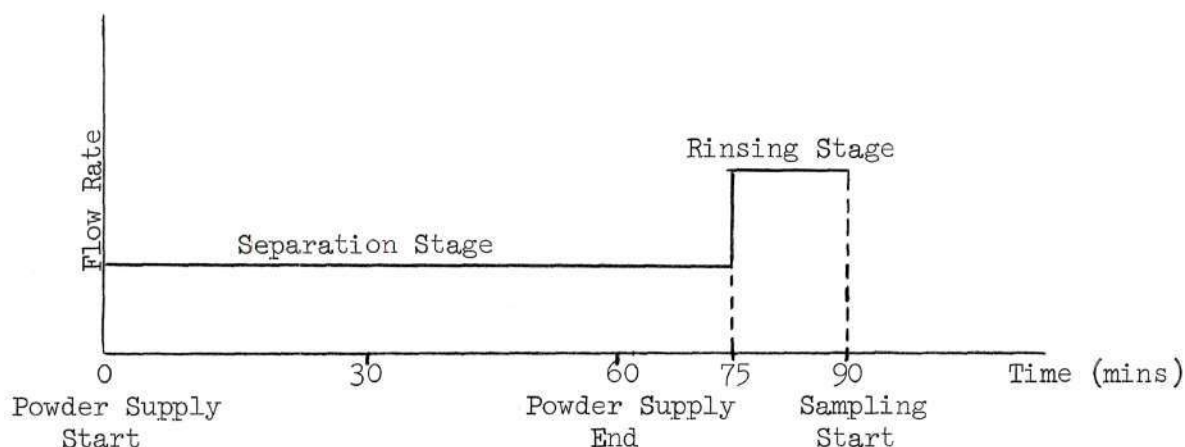


Figure 20. Flow Rate versus Time Schedule for Four Grams of Flint Silica Powder.

It was expected that at this higher flow rate particles in the sections would rise and block the upper sieves, but it was observed that the particles generally followed a circular flow pattern in each section as shown in Figure 21. Also shown in the figure is the flow pattern for the separation stage. Particles that did block the sieves during rinsing were recovered by returning the flow rate to its original value one or two times.

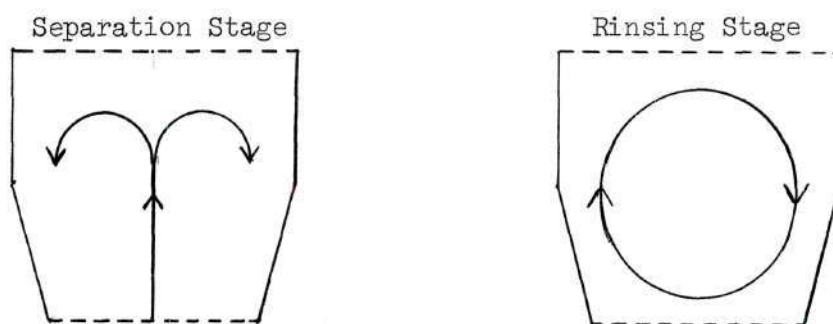


Figure 21. Flow Patterns During Operation.

Although it was found that the first screen was most easily blocked because Section 0 has the highest concentration and the smallest

screen area for particles passing, the optimum particle supplying rate was found to be about four grams per hour for glass beads and flint silica for the column system employed in this work.

Kaye⁽²⁰⁾ stated that the sieve surface was covered only instantaneously with particles and that as soon as the fluid flow was stopped the particles fell back into the sump of the felvation column. Throughout this study it was found that, even if the fluid flow was stopped, all particles did not fall back and that inevitably some particles hang in the sieves.

Vibrating and tapping the inlet tube to the tower to produce a pulsating flow sometimes worked well to keep sieve apertures free of particles. Blockage was more likely to occur in the separation stage than in the rinsing stage, the reason being that in the separation stage many more particles were trying to pass through the sieves at one time. Blockage clearly reduced the sharpness of the fractionation. Most of the blockage was prevented by adding vibration and by creating pulsing flow.

Sieves were little damaged by felvation. Water was taken out through both sampling tubes and the inlet tube after sampling, and this water falling through the tower put some strain on the sieves. But as the water level was reduced slowly, this strain was so little that the damage was essentially negligible.

CHAPTER VI

CONCLUSIONS

It is concluded that:

- (1) Constant-flow felvation is a very valuable technique, providing a sharp and clear particle separation.
- (2) Felvation is superior to elutriation in that it requires less time, the flow rate is not so critical, the flow need not be laminar, and the size distribution obtained can be predicted with greater reliability.
- (3) Felvation is also superior to dry sieving in that fine particles which can hardly be removed by sieving can be very easily eliminated. Also recovered particle fractions are more nearly uniform.
- (4) Constant-flow felvation is easier to control than variable-flow felvation.
- (5) Vibration by ultrasonic generation is useful in preventing particles from blocking sieves and in suspending them in the fluid. Vibration also helps by separating coagulated particles.
- (6) Sieves function almost at maximum efficiency as go-no-go gauges in felvation, i.e., particles which should pass through a sieve pass through it and those which should not are retained.
- (7) Powder should be supplied at a steady and controlled rate.
- (8) Rinsing is useful in removing the last remaining particles, and it makes good possible separation.

(9) The manner of operation described herein permits the number of sections to be varied and any desired number of fractions to be taken.

(10) The more uniformly distributed are the openings in the sieves, the more uniform is the separation that can be obtained.

CHAPTER VIII

RECOMMENDATIONS

(1) In this thesis, only small amounts of powder were employed to determine the degree of separation attainable by felvation. It would be possible to fractionate more powder with the same equipment. First, the outlet of the tower should be closed and the outlet of Section III (see Figure 1) opened. A higher flow rate than the calculated Stokes' flow rate is then fed into the tower, the fluid leaving the tower only through the one outlet. This higher flow rate is continued until all particles in Section III are removed. When this point is reached, the first outlet is closed and the outlet of Section II is opened. By repeating the same thing for Sections II, I, and O, all the particles in the tower are removed. After this point has been reached, powder is again fed to the tower and the same procedure is repeated.

(2) If this equipment is scaled up, sieves with more area must be used. In order to use greater areas, it may be necessary to devise sieve supports in both directions, i.e., up and down.

(3) As noted, tapping the rubber inlet tube helped avoid the blockage of sieves by particles. Using a true pulsing flow generator in conjunction with vibration should be investigated.

(4) It is not possible at this point to fix the diameter of particles that should be chosen in designing felvation columns for the best fractionation. It seems, however, that a diameter equal to the normal

size of the upper screen or about two microns less is best for the range of the sizes employed in this study. As a first try in this work, diameters approximately intermediate between the two upper and lower sieves were chosen, but it was found that this resulted in too much sieve blockage.

(5) Although ideal dry screening was used to predict the result obtained with felvation, it would be better for practical use to calibrate sieves for each material and for each operating method in which they are to be employed.

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